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Methods

Using LEDs: drivers and dimming

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Light emiting diodes (LEDs)

In this article I describe how currently available LED drivers and computer interfaces make it extremely easy to build custom light sources. In particular light sources useful for photobiological experiments. Currently in electronics "functional building blocks" have become very common for high power devices as in the 1970's logic and low-power analogue integrated circuits. Logic integrated circuits made it feasible to build the first personal computers. Some of the current solid state LED drivers make it possible to assemble custom circuits for driving power LEDs using very few parts. However, before one can take full advantage of these LED drivers some understanding of how LEDs work and the methods commonly used for adjusting their radiation output is needed.

LEDs are diodes, devices with two electrodes and polarity. Electrons move through a diode only in one direction, and need to be always driven by direct current. Under typical use within the recommended current range the amount of light emitted by LEDs is approximately proportional to the current flowing through them, although conversion efficiency slightly decreases when LEDs are driven their *maximum current* specification.

LEDs are available as components, as bulbs and as whole lamp fixtures. Bulbs and light fixtures have built-in drivers and can be connected directly to the mains power line. As the driver is built-in, in general bulbs and fixtures allow only limited control of light output and are available only for certain spectral characteristics (e.g. "warm white" or 2700 K to 3000 K, "cool white" or 4000 K and more rarely "daylight" or 5000 K to 6000 K) and emission geometries (e.g. with reflectors:"spot" or 20–30 degrees, "flood" or 60–65 degrees, or a nearly spherical shape). The variety of LEDs available as electronic components is enormous, both in specifications and type of "encapsulation"—meaning the "enclosure" they are permanently encased in. High power LEDs tend to be arrays assembled from multiple lower-power dies or chips—meaning the actual semiconductor devices (See Table 6.2 for definitions of electronics-related terminology) . Currently single-die LEDs of up 4 W are available. Dies can be densely packed onto a small carrier board, or chip-on-board (COB) packages. Latest state-of-the-art types can be so densely packed as to reach very high emittances (for example white COB LEDs of type NVEWJ048z-V1 from NICHIA pack 168 W of LED power on a board 24 mm × 24 mm, with an output of more than 10 000 lm). Such extreme concentration of heat production requires special handling to avoid the destruction of the devices. More conventional arrays are less densely arranged within the packages or they can be arrays of individually packaged LED dies soldered onto a carrier board—usually with a metal core that ensures good heat conduction into a heatsink for its dissipation by radiation and convection (Figure 6.1).

The technology for making LEDs emitting

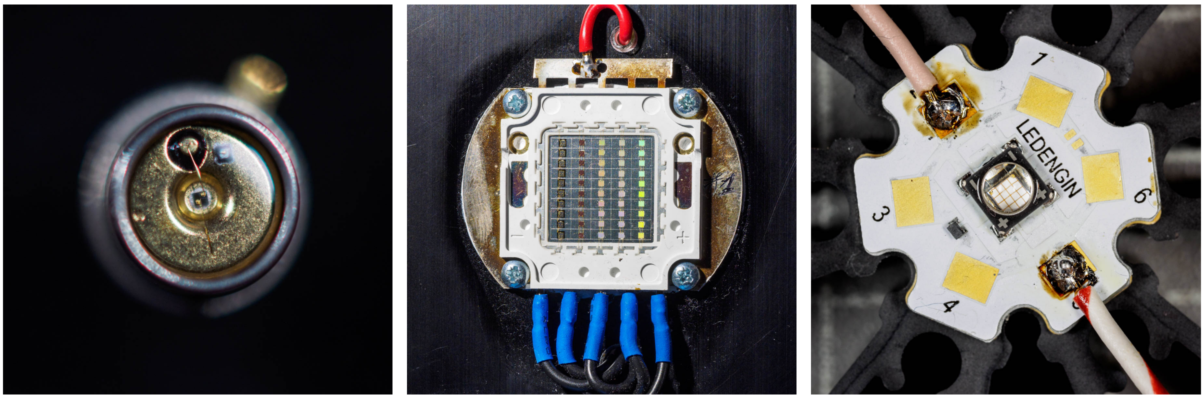

Figure 6.1: Light emitting diodes. a) The first UV LED sold commercially (top view). The LED die can be seen at the center below the flat window (type NSHU550E, Nichia, Japan), b) A custom assembled array with 50 1 W LED dies. This array has five channels, each one with different dies. One of the channels emits at 365 nm. (Shenzhen Weili, Shenzhen, China) c) A 4 W high power LED at 365 nm mounted on a star-board (type LZ1-00UV00 LED Engin, USA).

in the ultraviolet region of the spectrum has remained behind that of LEDs emitting visible and infra-red radiation. LEDs emitting at different wavelengths are based on different crystalline chemical substances. The principle by which all LEDs emit radiation is the same, but it is not equally easy to make LEDs emitting at all wavelengths, in particular efficiencies vary widely depending on the materials used. In recent years UV-A and violet LEDs with peaks of emission between 365 nm and 410 nm have become available with conversion efficiencies comparable or in some cases even better than that of blue and other visible LEDs. Prices for these types of LEDs are also comparable to the now very low cost of visible LEDs.

At shorter wavelengths the situation is not that favourable, yet. The company pioneering short UV LED technology was SETi (Sensor Electronic Technology Inc., Columbia, SC, USA). It was acquired by its competitor in UV LED technology, (Seoul Viosys, Gyeonggi-do, Republic of Korea) which is now the main supplier of short-UV LED chips. For some years LEDs emitting at shorter and shorter wavelengths have been developed—with 255 nm LEDs commercially available at the time of writing—, but most of these LEDs were of so low power as not to be useful for plant photobiology, or so expensive for higher optical power ones as to be of limited use except under laboratory conditions. High power UV-B LEDs, like those from SETi, had very high electrical power consumption but very low UV-B radiation output. While the best commercially available UVA LEDs at 365 nm can convert more than half of the electrical power into radiation, the most efficient UVB LEDs at 310 nm available commercially until two years ago had a conversion efficiency of the order of 0.1%. Furthermore, these LEDs had an output that decreases significantly with use and a rather short rated life of only about 2000 h and prices in thousands of euro. In the last couple of years more efficient and cheaper LEDs emitting at wavelengths shorter than 365 nm have become available making their use in plant photobiology research feasible.

Marktech's new 340 nm LEDs with an electrical power of 2 W and emitting 55 mW of radiation—an efficiency of 1.5%—are available for less than 50 € (type MTSM340UV-F5120S, Marktech Optoelectronics, Latham, NY, USA). The same company sells 310 nm LEDs with electrical power of 0.21 W emitting 2 mW of radiation—an efficiency close to

1%—also for close to 50 € (type MTSM310UV-F1120S). A different company, RayVio, has announced 280 nm and 310 nm LEDs with electrical power of 6.4 W emitting 50 mW of radiation—an efficiency of 0.85%—(types RVXP4-280-SB and RVXP4-310-SB, RayVio Corporation, Hayward, CA, USA). The 280 nm type is already available at 170 €, while the 310 nm type is not yet available. In contrast to most other types of LEDs, the radiation output of RayVio's UVB LEDs decreases drastically with increasing temperature. In the case of these new devices the expected life is not yet provided and technical specifications are still labeled as "preliminary". Seoul Viosys together with SETi offer also newer types of 310 nm LEDs, such as type CUD1AF4C with an electrical power of 0.48 W emits up to 8 mW of radiation—an efficiency close to 1.7%—and type CUD1AF4D, four times as much. Furthermore, type CUD1AFMA, a 310 nm LED chip-on-board package with 64 chips, has an radiation output of 80 mW, and type CUD1TFMA with 256 LED chips has an output close to 0.5 W of UVB radiation.

Dimming of LEDs

Depending on the power source used, the radiation output from LEDs may vary in time at a relatively high frequency. Both mains supply frequency and the approach used for adjusting the radiation output or *dimming* may cause variation in output in most cases invisible to the human eye. Use of LEDs is becoming pervasive in buildings and gradually increasing for commercial plant cultivation. They are also becoming common in controlled environments used in plant research. Dimmers are frequently used to adjust the light level in households, offices, commercial spaces, and currently also in growth chambers and growth rooms. Even special LED lamps sold for studio and on location video and photography are in most cases dimmable.

There are two main approaches to dimming: constant current (CC) and pulse width modulation (PWM). The later approach is more frequently used, as achieving high efficiency in a CC driver requires a more complex and expensive electronic circuit than PWM. There is third approach in use, based on the use of phase shift dimmers, and useful when "retrofiting" LEDs as replacements for incandescent lamps. Phase shift dimming is similar in PWM, but instead of using square pulses, they "chop" part of each sinusoidal half cycle of the mains AC supply. As rarely used for new installations, I will only discuss the first two LED-specific dimming approaches. Driving LEDs at constant voltage is in general to be avoided as current flow through LEDs tends to increase exponentially with the increase in voltage. In addition as current at a given voltage increases when the LED gets warmer, this can lead to feed forward and the destruction of the device. For very low power LEDs in most cases resistors connected in series with LEDs function as current limiters.

When LEDs are driven at constant current a circuit adjusts voltage in such a way that current flow through the LED remains at a constant value. As the output of LEDs is approximately proportional to the current flowing through them, by decreasing the current (the flow of electrons) we can decrease the light output (the flow of emitted photons). Good quality LEDs drivers can regulate the current to a tolerance better than ±1%, giving extremely steady illumination (Figure 6.2).

Pulse width modulation, in everyday words means that the LEDs are very rapidly switched on and off. Light output alternates between maximum output and no output (Figure 6.2). The combined duration of a pair of light plus dark periods remains constant, but their relative duration is adjusted to achieve dimming. When we plot the light output as a function of time it is a train nearly of square pulses. The average photon irradiance depends on the ratio between the light

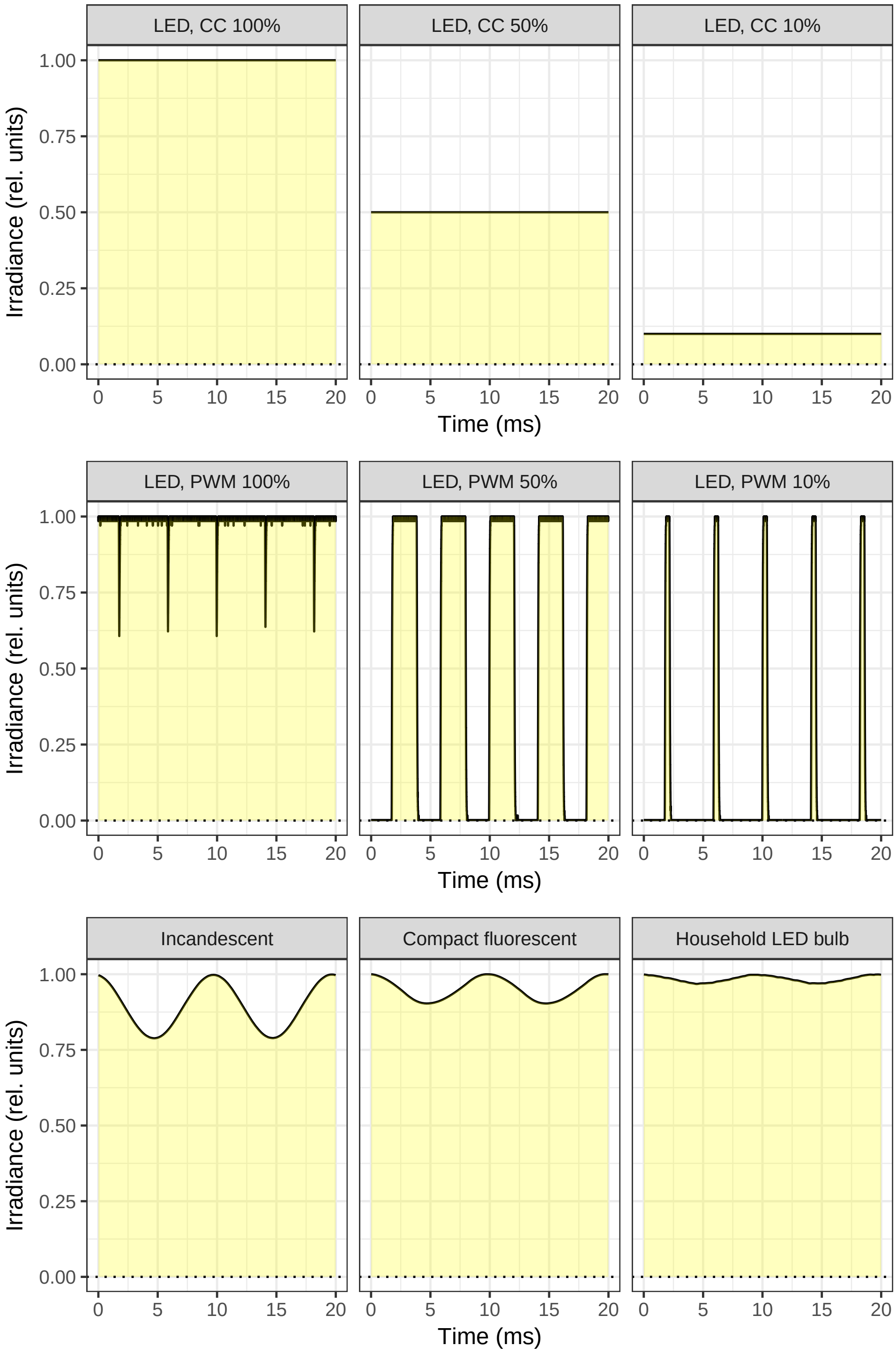

Figure 6.2: LED dimming. Top) Continuous current dimming. Middle) Pulse width modulation dimming. The relative light output from LEDs at 100% output, and dimmed to 50% and 10%. Bottom) Light output from three types of common household bulbs, not dimmed. The time scale of 20 ms is equivalent to one cycle of 50 Hz mains power as used in Europe. Measured with a TSL251R (or TSL252R, for high frequency) light-to-voltage sensor connected to an oscilloscope (Picoscope 2204A, Pico Technology).

periods and the whole cycle period—i.e. the frequency remains constant, what changes is the width of the "square-wave" shaped peaks. Hence, pulse width modulation. The frequency used can vary very widely, from close to 100 Hz (10 ms per cycle), the minimum that humans will not perceive as flicker, to much higher frequencies of the order of 10 to 100 kHz.

While for human vision 100 Hz is fast enough, for light sources used in photography this is not enough to avoid uneven exposure. An example of use of PWM at high frequency is the Amaran AL-H9 LED light source (Aputure Imaging Industries, Bao'an, Shenzhen, China), which uses a frequency of 40 kHz (0.025 ms per cycle). This is unlikely to cause uneven exposure because a shutter speed of 1/10 000 s is enough to ensure that a single exposure encompasses four pulses of light.

LED lamps sold as substitutes for incandescent and compact fluorescent lamps, as well as these older types of bulbs they replace tend to have a light output that to variable extent changes cyclically in time. As mains power is alternating current (AC), in each cycle there are two half cycles, one negative and one positive. Both half cycles drive the emission of light, but twice in a cycle voltage becomes zero, resulting in light output pulsing at twice the frequency of the mains power (Figure 6.2).

Although we do not see high frequency flickering, a digital or film camera can see it at some shutter speeds (Figure 6.3). Focal-plane camera shutters use a moving slit for short exposure times, in other words, the whole frame is not captured at the same time. I have earlier discussed dimming of LEDs and line-frequency oscillations in artificial illumination in relation to photography (Aphalo 2017a,b).

In the case of plants, CC is closer to sunlight than PWM. Within canopies sunflecks con be of short duration but the alternation is between two irradiances, none of which is close to zero. With PWM dimmed LEDs, the alternation is between light and darkness, which does not occur in plant canopies. Effects of pulsed illumination on plants has been studied in relation to sunflecks, but the results from these studies do not necessarily apply to PWM given the broad range of frequencies in use and the presence of dark periods. This is a problem that needs to be studied, and that can be studied using the circuits described later in this article.

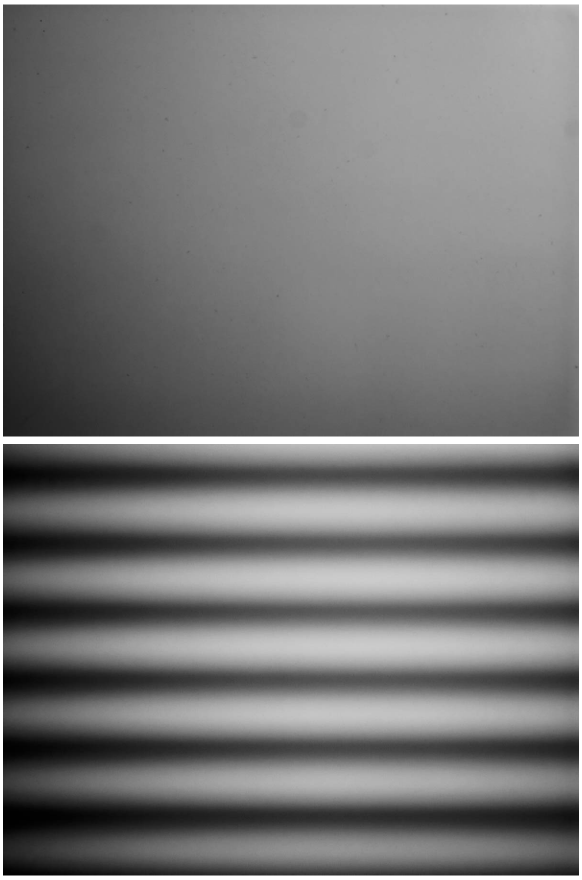

Figure 6.3: Photograph of a plain white wall illuminated with a LED dimmed using pulse width modulation. When taking this photographs to my eyes the wall was evenly illuminated; top) Shutter speed 1/10 s, bottom) shutter speed 1/1250 s. The two photographs have been identically edited so as to increase their contrast.

Building an UV, VIS or IR radiation source using LEDs

We will present two similar circuits, the first one is suitable for manually controlled dimming using the constant current (CC) approach. The second circuit allows dimming using both approaches, even simultaneously, CC and PWM. Dimming in this case can be controlled locally using a computer or microcontroller connected via USB, or remotely through the internet to any device with a web browser. Both circuits can run on batteries or with a mains powered DC source. No wiring is needed on the mains power side of the circuit allowing assembly by users not officially qualified to do electrical installations in countries like Finland where strict legal regulations are in place. Many variations are possible when using DC/DC LED drivers to control multiple LEDs (see RECOM 2017).

The example circuits use a driver that limits its maximum current to 0.7 A, the maximum allowed current limit for the types of LEDs used here. As a safeguard I prefer to use drivers that have a "hard-wired" maximum current limit at a value that will not destroy the LEDs being used. Variants within the same series of drivers are available with different values for this limit (In the case of RECOM's RCD-48 series, 0.35 A, 0.50 A, 0.70 A, 1.00 A, and 1.20 A), and using these variants does not require any changes to the circuits described here (see RECOM 2016). It is possible to use drivers with a higher maximum current rating than what is allowed for the LED being driven, but then *the user should remember* not to ever use a *soft* current setting higher than what the driven LEDs tolerate.

The DC LED drivers used here do not require external components to function, but they do required an external signal to control dimming. For manual control a potentiometer (variable resistor) is needed for adjustment of constant current dimming, while PWM dimming is not possible without a separate source of pulses. The potentiometer used in the example allows exactly repeatable settings. However, if repeatability of settings is not a requirement, it can be substituted by a cheaper potentiometer of the same resistance value. For permanent installations using a printed circuit board or a prototyping perforated board and soldering all components is best. For semi-permanent assembly the use of quick connectors as shown in these examples is adequate while making assembly very easy, reducing the soldering of wires to what is required for connecting the LED itself.

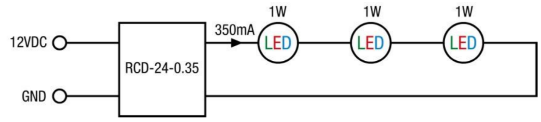

Figure 6.4: Dimming circuit based on an RCD series DC/DC LED driver with a variable number of LEDs connected in series. Reproduced from RCD white paper.

The chosen LED drivers can regulate the voltage output to the LED(s) between 2 V and 56 V while keeping the current flow at the set value. This makes it possible to drive with the same circuit anything from a single LED to more than 20 LEDs connected in series, and also LED arrays specified to require up to 56 V (Figure 6.4). The DC input voltage supplied determines the maximum achievable output voltage and it must be within 9 V and 60 V. Within this range, the input voltage needs to be at least 4 V higher than the output voltage required to drive the LED at maximum rated current. All component specifications are subject to tolerances, i.e. values are given as ranges of possible values, and for this reason it is usually wise to slightly "over-specify" components when designing a circuit.

LEDs, even modern very high efficiency types, have an efficiency of at most 60%. In the case of LEDs emitting at wavelengths shorter than 365 nm typical efficiencies are 2% at most. The power that is not emitted as visible or UV radiation becomes thermal en-

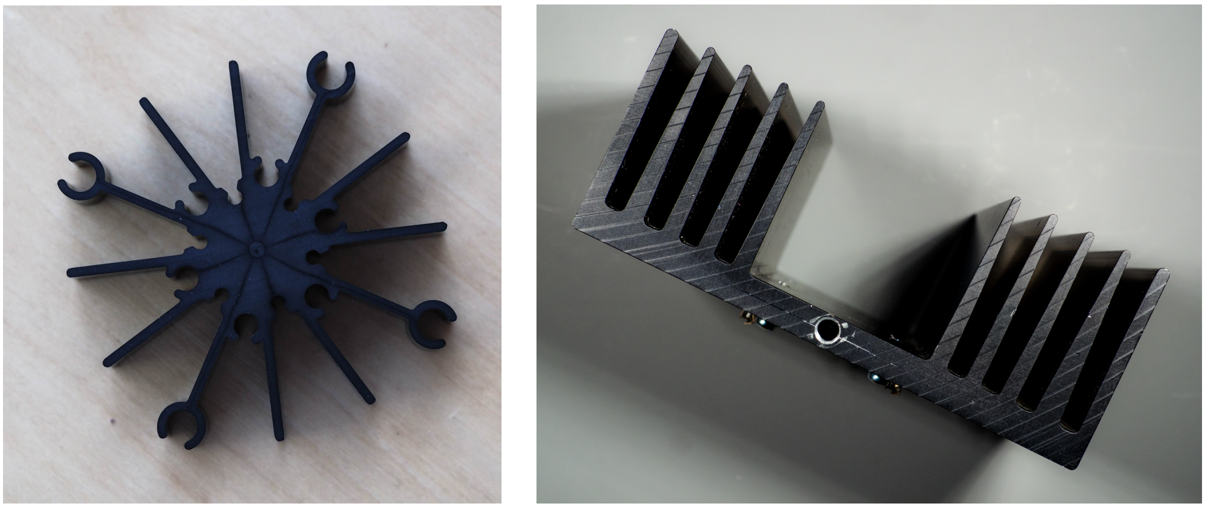

Figure 6.5: Heat sinks. left) A heat sink for medium power LEDs mounted on star boards—this type is nice as it can be easily fastened with M5 screws taking avantage of the split holes at the tip of the fins. right) A generic heat sink for high power devices.

ergy that heats up the LED chip. LED chips get destroyed if their temperature raises above 100 to 125 °C, and because of this reason power LEDs require cooling. The simplest type of cooling devices are passive heat sinks. Heat sinks are usually made of aluminium, which has high thermal conductivity, and are anodized black to enhance emissivity. The shape of heat sinks varies a lot, but all of them have fins to increase their surface, as both thermal radiation emission and convective cooling depend on the surface area through which energy is exchanged (Figure 6.5). In contrast, the RECOM RCD-48 driver has very high efficiency of up to 96% both when dimming through PWM and CC, and consequently does not require a heat sink for its cooling.

The LED drivers in the RCD-48 series come not only in different maximum current variants, but also in different packages (Figure 6.7). Most of the available packages are plastic, but differ in whether they have pins suitable for installation in a printed circuit board or insulated wires suitable for direct wiring. For prototyping, the first type can also be used in a “breadboard”. Within this series, the type with the highest current rating is encapsulated in a metal package as metal conducts heat better than plastic.

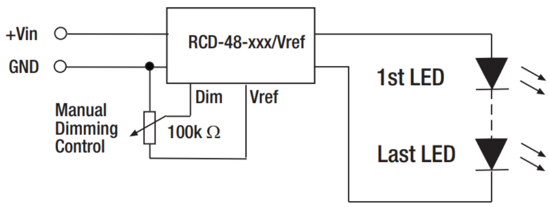

Figure 6.6: Analogue dimming circuit based on an RCD-48 DC/DC LED driver. Reproduced from data sheet.

Constant current dimming with manual control

We need only three electronic components in addition to the LED(s): a) a DC power supply or battery, b) a DC/DC LED driver and c) a potentiometer (variable resistor with three terminals). Which power supply to use will depend on the number and type of LEDs to be powered. I have used 12V DC power banks, and AC mains to 9 V DC, 12 V DC and 36 V DC power supplies, with current ratings between 1 A and 4 A. As DC/DC drivers, those in the RECOM RCD-48 family are very versat-

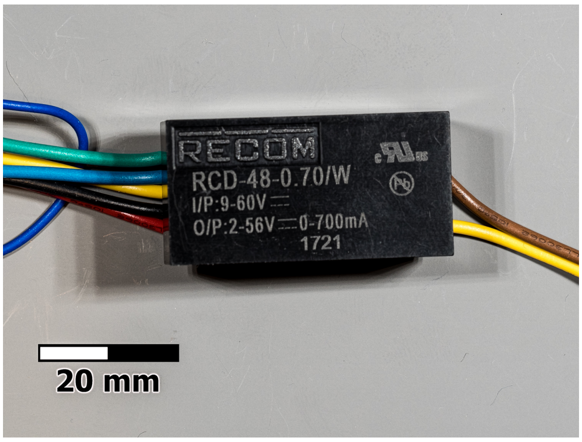

Figure 6.7: A direct current to direct current high precision LED driver from RECOM.

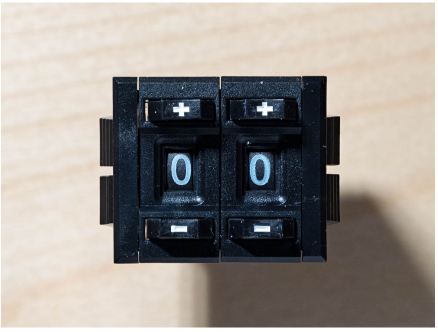

Figure 6.8: A 100 KΩ precision potentiometer that is set by means of two push-buttons per digit.

ile and the same type will be used in all examples: RECOM RCD-48-0.70-W which has a maximum current rating of 700 mA and has wire leads instead of the more usual pins for installation in printed circuit boards (Figure 6.7). Most potentiometers with a resistance of 100 kΩ could do the job in these case. I chose a 2-digit type with push-buttons which allows 100 different repeatable settings, which I find convenient (Figure 6.8).

The heart of the circuit is the LED driver. This integrated module has seven wires, two for DC input, red (+) and black (−), to be connected to the power supply, and two for regulated DC output (brown (−) and yellow beside brown (+) to be connected to the LED(s). The three remaining wires are used for control. The blue (+) one is a digital input which allows PWM dimming and/or ON/OFF switching of the current fed to the LED. The green (+) is an analogue input, accepting a voltage between 0 V and 5 V which allows constant current dimming. The yellow wire in-between the black and blue wires is a reference output at 5.1 V, which can be used to control analogue dimming with passive components like resistors and potentiometers.

Dimming controlled with computer, tablet or phone via USB

For this type of control there are many options, as what we need is to generate a voltage between 0–5 V for constant-current dimming, or a train of square wave pulses for PWM. I have chosen two very small but high quality modules from Yoctopuce for maximum flexibility (Figures 6.9 and 6.10). The module called Yocto-PWM-Tx generates pulses at a frequency and duty cycle that can be easily set using a web browser. The range of achievable frequencies is very broad. The module called Yocto-0-10V-Tx generates a tightly regulated DC voltage of any value between 0 and 10 V, and can also be easily set using a web browser (Figure 6.11). Each of these Yoctopuce modules has two independent channels, and consequently is able to control two independent groups of LED drivers. Tens of LED drivers to be dimmed simultaneously can be connected to each channel of the modules. Both modules are powered through their USB connections to the device used as controller but the "two sides" of the interface modules, one connected to the USB port, and the other to the LED driver are electrically isolated. Isolation in the Yoctopuce modules ensures that the host computer will not be perturbed or damaged if the LED driver circuit fails or is wrongly connected. Although I describe here control through a web browser, the modules can be also accessed through user-written computer programs that "talk" to libraries provided by Yoctopuce.

This same circuit when used with a com-

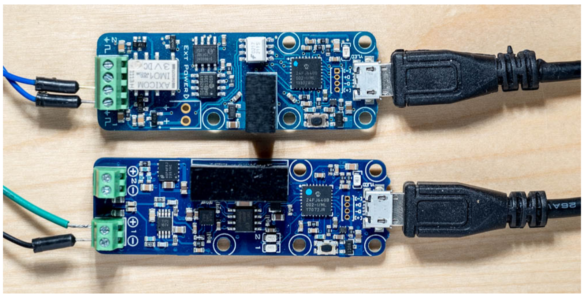

Figure 6.9: A Yocto-0-10V-Tx module and a Yocto-PWM-Tx module.

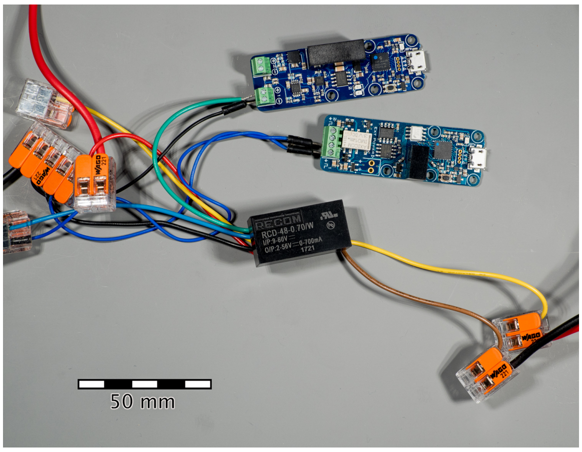

Figure 6.10: Assembled control circuit, using Wago wire connectors for easy of assembly. The components are the same as shown in Figures 6.7 and 6.9. The micro-USB cables are not plugged in.

puter (any computer, including microcontroller boards like Raspberry Pie and Beaglebone) can achieve more elaborate types of control by addition of sensors and writing of suitable software. It is needed, however, to approach this type device development keeping in mind reliability. Any computer system that crashes even once in a few months, is unsuitable for any device that needs to reliably function without interruption for months if not years.

Dimming controlled with computer, tablet or phone via LAN or Internet

The same modules, instead of being connected via USB to a computer, can be connected to a Yocto-hub and this connected via ethernet, Wifi or GSM to a LAN or a router (Figure 6.12). With appropriate firewall settings everything works as described in the previous section. However, if ports cannot be opened in a firewall, other methods of remote access to the modules are available. The Yoctopuce modules use high quality industrial grade electronic components in most cases rated for operation under -40 C to +80 C. Administration, including firmware updates can be done remotely. Access can be password protected.

Suppliers

I have bought most parts from large electronics parts distributors, except for the YoctoPuce modules, which I bought directly from the manufacturer. I list in Table 6.1 the manufacturers and distributors of the parts used.

Further reading

The book *Applied Electronics for Bioengineers: an introduction* (Karplus 2017) is a good place to start if you want to learn about electronics with a focus on instrumentation and simples device used in biological research.

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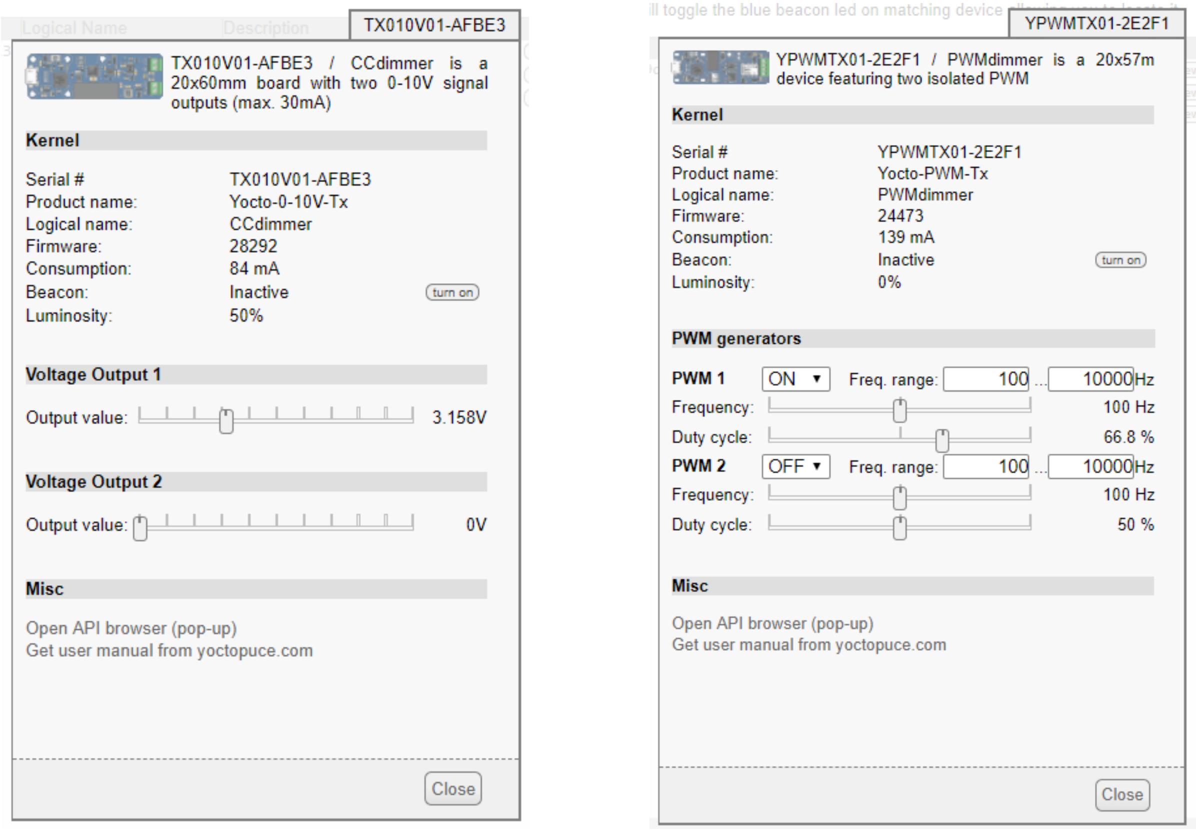

Figure 6.11: The control interfaces of a Yocto-0-10V-Tx module and of a Yocto-PWM-Tx module as they are displayed on a web browser. The interface is identical whether the modules are connected locally via USB to the computer or through an ethernet, Wifi or GSM YoctoHub accessed remotely through the internet (WAN) or a local area network (LAN).

Table 6.1: Suppliers of electronic components and UV LEDs.

Supplier	URL	components
Bourns	http://www.bourns.com/	high precision potentiometers
Digi-Key electronics	https://www.digikey.com/	elec. comp. distributor
LED Engin	http://www.ledengin.com/	UVA and VIS LEDs
Marktech optoelectronics	http://www.marktechopto.com/	UVB and UVA LEDs
MEAN WELL	http://www.meanwell.com/	LED drivers and power supplies
Mouser electronics	https://eu.mouser.com/	elec. comp. distributor
NICHIA	http://www.nichia.co.jp/en/	UVA and VIS LEDs
OHMITE	http://www.ohmite.com/	heat sinks for star board
RayVio	http://www.rayvio.com	UVB and UVA LEDs
RECOM Power	https://www.recom-power.com/	LED drivers and power supplies
Roithner laser	http://www.roithner-laser.com/	LED and laser distributor
Seoul Optosys	http://www.seoulviosys.com/en/	UVC, UVB and UVA LEDs
t-Global technology	http://www.tglobaltechnology.com/	pre-cut heat-transfer pads
Wakefield-Vette	http://www.wakefield-vette.com/	heat sinks
Yoctopuce	https://www.yoctopuce.com/	USB interfaces and sensors

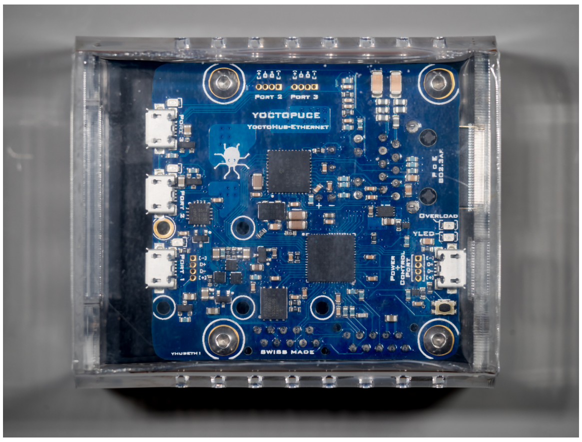

Figure 6.12: A Yoctopuce ethernet hub.

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Table 6.2: Glossary of terms frequently used in electronics.

Term	Meaning
LED die	The actual piece of specially processed semiconductor substance that emits photons when electrons flow through it.
LED chip	see LED die.
Semiconductor	Substance at the boundary between metals and non-metals. Electrical conductivity depends on "impurities" in the crystals.
Dimming	Method used to decreasing the radiation output from a lamp or LED by adjustment of the average rate of flow of electrons through the lamp or LED.
Data sheet	The document published by a manufacturer describing the technical specifications of an electronic device, sometimes including very simple examples of their use.
Application note	A document published by a manufacturer describing in detail examples of the use of an electronic device.
Software driver	A program in a computer that provides a way for controlling an electronic device through another computer program which provides a user interface.
Breadboard	A board in which electronic components and wires can be plugged in to assemble a circuit. In general used for temporary assembly during testing of a design.
Perfboard	A perfboard or prototype board is a generic printed circuit with rows of holes connected be electrically conductive copper strips or lanes layered on top of an insulating material. Assembly requires soldering and breaking/cutting some of copper strips. Usually used for permanent assembly of simple one-of-kind circuits or prototypes.
Printed circuit	A circuit board where the copper lanes and locations and sizes of perforations or attachment pads have been designed for a given circuit and usually photo-etched from a board of insulating material fully covered with a copper layer. Assembly is by soldering of components. Used in different variations all the way from one-of-kind circuits to series of millions of identical electronic devices.